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Linear Vent Area of the Soldier Meadow Tuff, an Ash-Flow Sheet in Northwestern Nevada

ABSTRACT

The Soldier Meadow Tuff of late Miocene age was erupted from a linear vent area in northwestern Nevada. Numerous ash flows representing about 50 cu km of magma were erupted, followed by less energetic eruption of a small volume of air-fall tuff, which is welded near the vents. The vents then served as feeders for lava flows unquestionably comagmatic with the tuffs. Flow foliation in the lava flows defines four vents aligned in a north-south direction, and part of the internal structure of one of the vents has been exposed by faulting and erosion. The distribution pattern of the ash-flow sheet, the distribution and size variation of xenoliths, and the absence of a cooling break between tuff and lava all support this interpretation. The tuff and lava consist of peralkaline rhyolite (comendite) and are virtually identical in mineralogy and chemistry. Neither caldera collapse nor local subsidence occurred after eruption of the Soldier Meadow Tuff. The arrangement of vents parallel to a range-front fault trend implies control of alignment by extensional Basin-Range faults.

The tuff of Trough Mountain, an earlier unit of phenocryst-poor, comendite ash-flow tuff of more limited volume and extent, appears to have erupted from a vent area which is elongate northward and nearly coincident with that of the Soldier Meadow Tuff, as indicated by thickness, areal distribution, welding of air-fall tuff, and distribution of xenoliths.

INTRODUCTION

The possible type or types of eruptive vents for large volumes of silicic ash-flow tuff have long been the object of speculation as well as intensive field investigations, particularly in the western United States. However, definite vents or vent areas have not yet been recognized for most relatively well preserved ash-flow sheets. Almost all ash-flow tuff sheets which have been related to a specific source area are associated with collapse calderas. There is widespread agreement (for example, Reynolds, 1956; Smith, 1960a; compare Williams, 1941) that ash flows related to calderas have erupted either from central vents or, more commonly, from concentric or radial fissures. These fissures may be caused by doming above a rising or swelling magma body (Smith and Bailey, 1968, p. 637). Because of subsequent caldera collapse, as well as later resurgence, emplacement of stocks and ring dikes, or burial by later volcanic or sedimentary rocks, such vents are generally not preserved or exposed.

Smith (1960a) postulated that calderas or larger volcano-tectonic depressions would be found associated with the sources of ash-flow tuffs greater than several cubic miles in volume. However, careful mapping has failed to locate evidence of collapse structures for a number of large and small ash-flow sheets. Some workers have suggested that most large-volume ash-flow sheets not traceable to calderas were erupted from linear fissures (Mackin, 1960; Ross and Smith, 1961). They suggest that few such fissure vents have been found because they are commonly destroyed by associated faulting or are buried by the ash-flow sheets themselves (Smith, 1960a). Linear vent alignments and fissure eruptions, many without associated local collapse, are quite common for mafic and intermediate lavas and for small-volume silicic lava and pyroclastic rocks.

Possible feeder dikes for ash-flow sheets have been described by several workers. Taubeneck (1967, p. 1302–1303) discussed two Devonian dikes related to the Glen Coe cauldron which he feels "qualify as feeders for ignimbrites." These dikes contain breccia and have "pronounced flow structure," as well as the micro-

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scopic characteristics of welded pyroclastic rocks. Cook (1968) described two Oligocene plugs with vitroclastic to flow-banded structures and downward-steepening foliation. The plugs have zoned compositions transitional to that of a nearby ash-flow sheet of the same age. Within the area of distribution of a widespread Pliocene ash-flow sheet in Oregon, Walker (1969) delimited a central region in which foliation in the lower part of the tuff sheet is steeply inclined and stretched locally, and in one instance cuts across horizontal eutaxitic structure. Walker noted, however, that restriction of these flowage features to preexisting fault scarps and monoclinal warps introduces the possibility that at least some of the steep foliations were caused by post-emplacement compaction and flowage rather than by pyroclastic intrusion. Koronovsky (1971) described a 400-m-high vertical dike of flow-banded lava gradational upward to pumice, located in the northern Caucasus region, U.S.S.R. The dike bends 90° at its top to merge upward into welded ash-flow layers. Steeply foliated ignimbrite dikes which merge with an overlying ash-flow sheet at Sabaloka, Sudan, have been described by Almond (1971). A. C. Waters (Smith, 1960a, p. 818) described a similar dike several miles long from near Prineville, Oregon. Finally, several pyroclastic dikes and ring dikes, with steep to vertical eutaxitic structure but no related extrusive phases, have been described by Reynolds (1954, p. 591), Brock and Barker (1965), Branch (1966; p. 73, 74, 78), and Cook (1968). Features such as these, while not everywhere conclusive, are all nevertheless suggestive of vent or near-vent structures.

This paper describes the vent area of the Miocene Soldier Meadow Tuff at lat 41°28′ N., long 119°10′ W. in the northern Calico Mountains, northwestern Humboldt County, Nevada (Figs. 1 and 2). As presently exposed, this source area consists of several discrete, aligned vents for the lava flow in the upper part of the unit. However, during eruption of the ash flows which comprise by far the greater part of the formation, the vent area may have been either a continuous fissure or separate, aligned vents. No caldera formed during or after eruption (Korringa and Noble, 1970). Instead, the location and trend of the vent area is related spatially, and probably genetically, to a major Basin-Range fault trend (compare Wright and Troxel, 1971).

The terminology of pyroclastic deposits used in this paper is largely that of Smith (1960a, 1960b). A cooling unit is a sequence of tuff that cooled independently from adjacent sequences and thus is bounded everywhere by a complete cooling break (Noble and others, 1968). A simple cooling unit has no deviations from the ideal zonal pattern of welding and crystallization; a compound cooling unit has one or more such deviations, called partial cooling breaks, and may pass laterally from simple into compound and even into two or more cooling units (Smith, 1960b).

REGIONAL GEOLOGIC SETTING

Pre-Cenozoic rocks are not exposed in the northern Calico Mountains but occur in several of the surrounding ranges (Fig. 2), where metamorphosed volcanic and sedimentary rocks of Permian, Triassic, and Jurassic(?) age are intruded by granodiorite and quartz monzonite plutons of Jurassic and Cretaceous age (Willden, 1964; Smith and others, 1971).

The Cenozoic stratigraphy and volcano-tectonic evolution of northwestern Nevada are discussed by Bonham (1969), Noble and others (1970), and Noble and others (1973). The oldest known Tertiary deposits consist mainly of probable lower Oligocene and possible Eocene mafic and intermediate volcanic rocks in the southern Calico Mountains and northern Washoe County. During the early Miocene, the Ashdown Tuff (24 m.y. old), related ash-flow sheets, and the overlying domes and flows of the rhyolite of the Black Rock Range were emplaced (Noble and others, 1973). McKee and others (1970) have noted a hiatus in volcanic activity in the Great Basin from about 20 to 17 m.y. ago. Following this quiescence, a thick sequence of volcanic rocks was deposited over most of northwestern Nevada within the very short interval from about 16 to 15 m.y. ago. Dominant rock types are locally thick basalt flows similar to the Steens Basalt (Fuller, 1931; Noble and others, 1970), less voluminous intermediate lava flows, and abundant silicic tuff sheets and lava flows. The Soldier Meadow Tuff (about 15 m.y.), an ash-flow sheet with abundant quartz and sanidine phenocrysts, lies near the top of this sequence of rocks. It overlies the tuff of Trough Mountain near Soldier Meadow; beyond the extent of the latter formation, it rests on the Summit Lake Tuff (15.5 m.y.) and locally on other upper Miocene units (Noble and others, 1970). Near Soldier Meadow, the upper part of the Soldier Meadow Tuff is composed of comagmatic lava.

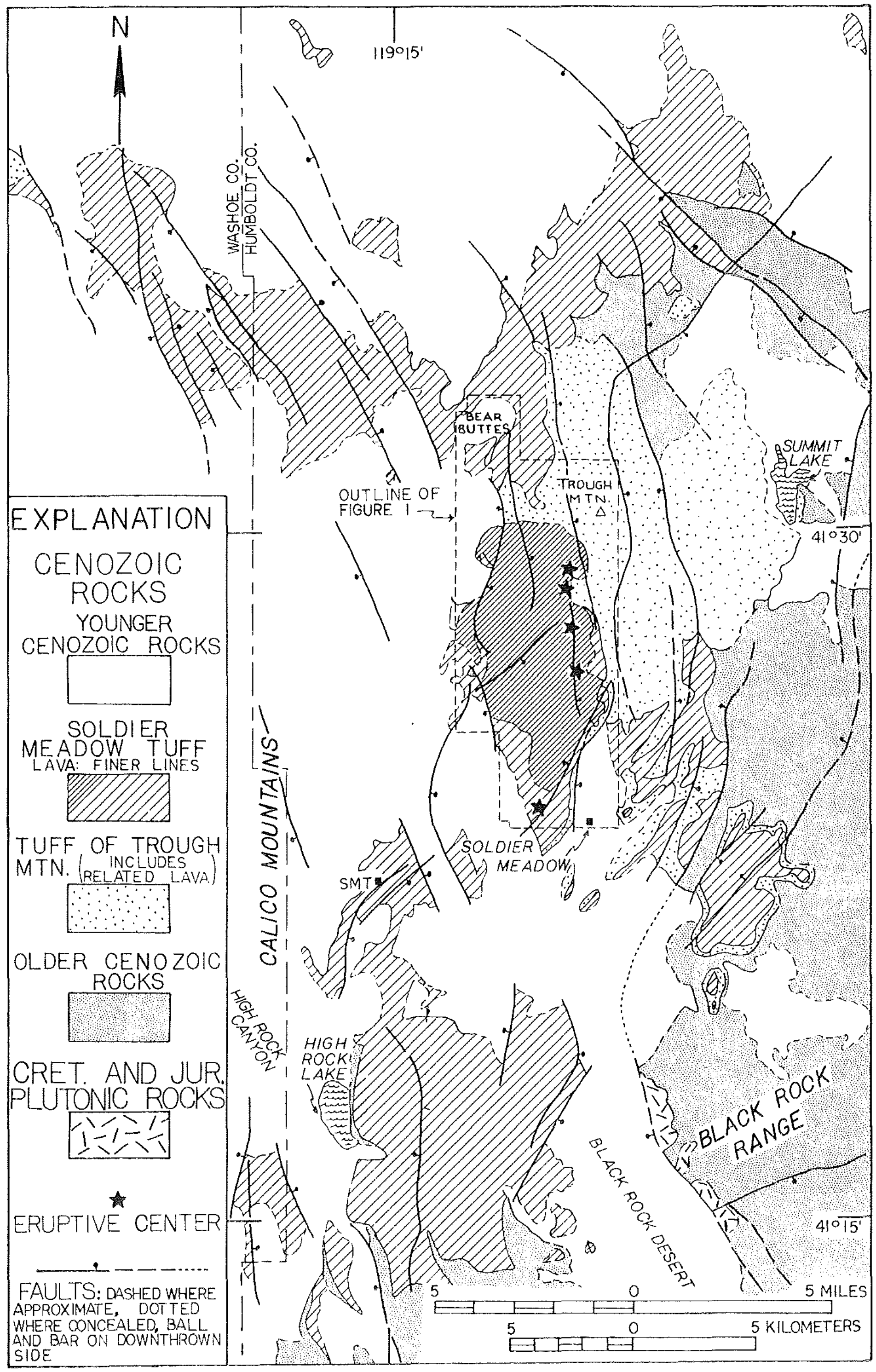


Figure 2. Generalized geologic map, showing distribution of Soldier Meadow Tuff, tuff of Trough Mountain, and major faults. Type section of the Soldier Meadow Tuff indicated by SMT. Reconnaissance mapping reproduced by permission of D. C. Noble.

Several welded ash-flow sheets of this late Miocene volcanic episode are distinctive and extensive enough to serve as stratigraphic markers and were used by Noble (Noble and others, 1970) to subdivide the Miocene volcanic rocks of the Calico Mountains, Black Rock Range, and Pine Forest Range to the north, and as evidence for inception of Basin-Range faulting in this region about 16 m.y. ago. Above the Soldier Meadow Tuff, in its northern exposures, there are dikes, domes, and flows of subalkaline and peralkaline silicic lava. Lithic-rich bedded tuff occurs locally above the Soldier Meadow Tuff, particularly west of Soldier Meadow. Mafic and intermediate lava flows, mainly of late Miocene and Pliocene age, intrude and overlie the other units on the west and north.

Present topography and drainage are mainly fault-controlled. Numerous landslides of various ages reflect the rapid rise of the ranges along boundary faults. Near the vents from which the Soldier Meadow Tuff was erupted, the major Basin-Range fault trend is north, with subsidiary trends N. 15° W., N. 40° E., and N. 60° E. One or more of these trends, or one N. 40° W., dominates throughout northwestern Humboldt and northern Washoe Counties, although some regions are relatively unbroken by faults. Most faults are normal, with dips of about 60° to 90° and offsets of several meters to a thousand meters. The northern part of the Calico Mountains is a tilted fault block, raised up along its eastern boundary; the southern Calico Mountains and Black Rock Range are both horsts (Fig. 2). Noble and others (1970) give examples of evidence that high-angle faulting in northwestern Nevada continued from late Miocene to Pleistocene and probably Holocene. No evidence was found for strike-slip movement on any of the local faults; rather, the dominant strain appears to have been approximately east-west extension (compare Hamilton and Myers, 1966, p. 509; Stewart, 1971; but see also Slemmons, 1967). Atwater (1970) relates such extension to plate tectonics, suggesting that Basin-Range faulting is under the influence of northwest-southeast shear in this region, which has been part of a broad transform zone between the Pacific and American crustal plates since about 20 to 15 m.y. ago. The continuing normal faulting in northwestern Nevada since about 16 m.y. ago is in agreement with that hypothesis. Christiansen and Lipman (1972) further relate this change in tectonism to a widespread change throughout much of the western United States, during early and middle Miocene, from dominantly calc-alkaline volcanism to eruptions of basalt or basalt plus more silicic and alkalic tuff and lava.

TUFF OF TROUGH MOUNTAIN

The tuff of Trough Mountain, which includes densely welded to nonwelded air-fall and ash-flow tuff, is found within about 35 km of Soldier Meadow Ranch in a region somewhat elongate northward (Fig. 2). The unit probably had an original areal extent of about 2,000 sq km. In many places, the unit consists entirely of nonwelded tuff, and its susceptibility to erosion makes impossible all but relative estimates of original thickness. However, exposures thicker than 50 m were not found farther than 10 km from Trough Mountain. Thicker sequences occur within this region; one section 125 m thick, but with no exposed basal contact, was measured. At least 325 m of tuff is exposed on Trough Mountain, near the center of the known extent of the unit.

Where welded, the tuff of Trough Mountain is gray, blue-gray, or tan and weathers pale brown to deep reddish brown. In any one section, there may be as many as eight cooling units, 1 to 10 m thick, of densely to poorly welded ash-flow tuff, in most instances separated by poorly welded to nonwelded ash-flow and air-fall deposits 1 to 30 m thick. Gas cavities are abundant in many of the cooling units. The welded tuff sheets are composed predominantly of glass shards. Collapsed pumice fragments generally comprise less than 10 percent of the rock, although pumice fragments make up about 40 percent of at least one distinctive cooling unit. The welded air-fall tuff is similar to ash-flow tuff but exhibits thin bedding with variations in pumice or lithic content (Fig. 3).

Air-fall deposits may be difficult to distinguish from ash-flow deposits. Air-fall materials may evenly mantle the surface upon which they are deposited, forming very continuous thin beds, while flows more commonly fill depressions. Materials deposited by base-surge commonly exhibit cross-bedding and disturbed bedding structures (Crowe and Fisher, 1973). Other ash-flow deposits may be massive, whereas air-fall materials are usually very well sorted and without cross-bedding. Commonly, fine ash is winnowed out during aerial transport (for example, the layers which are extremely rich in pumice in the Soldier

Meadow Tuff), and beds in air-fall deposits may be normally graded. Although such sorting also may be found at the base of some ash-flow deposits, many meters of air-fall tuff may be thin-bedded without intervening cross-bedded or massive deposits. However, near-vent air-fall deposits may contain abundant large lithic fragments which have been transported short distances by energetic eruptions; such deposits will not be well sorted. Interbedding of air-fall and ash-flow deposits should not be unusual; and in such circumstances, the origin of parts of a sequence may be in doubt.

Petrography

Phenocrysts in the tuff of Trough Mountain are mainly euhedral or broken sodic sanidine (0 to 7 percent; Korringa, 1972) but also include rare quartz and sodic amphibole. The groundmass is generally crystallized, consisting mainly of quartz and sanidine. Quartz, sanidine, and blue-green to yellow-brown pleochroic sodic amphibole occur as vapor-phase crystals in some pumice cavities. Nonwelded material is commonly glassy.

Two analyses of nonhydrated glass from the tuff of Trough Mountain are given in Table 1. These analyses indicate that the rock is a comendite, that is, a slightly peralkaline (atomic Na + K greater than Al) rhyolite.

Related Dikes and Flows

Volcanic rocks similar in appearance to the tuff of Trough Mountain underlie and intrude the unit, particularly in the region north and northwest of Soldier Meadow Ranch (Fig. 1). The rocks are light gray to tan and have pronounced flow foliation. Phenocrysts (0 to 5 percent) are mainly euhedral alkali feldspar as much as 1 mm long. Clinopyroxene phenocrysts, though more rare, are also found. The groundmass consists of sanidine and quartz crystals and minor clinopyroxene; some vesicles contain vapor-phase growths of quartz, sanidine, and sodic amphibole.

Vent Area

Several lines of evidence suggest that the tuff of Trough Mountain erupted from an elongate vent area nearly coincident with that of the younger Soldier Meadow Tuff. Welded air-fall tuff of Trough Mountain and large (>1 cm diam) lithic fragments in the unit are both apparently restricted to a north-south

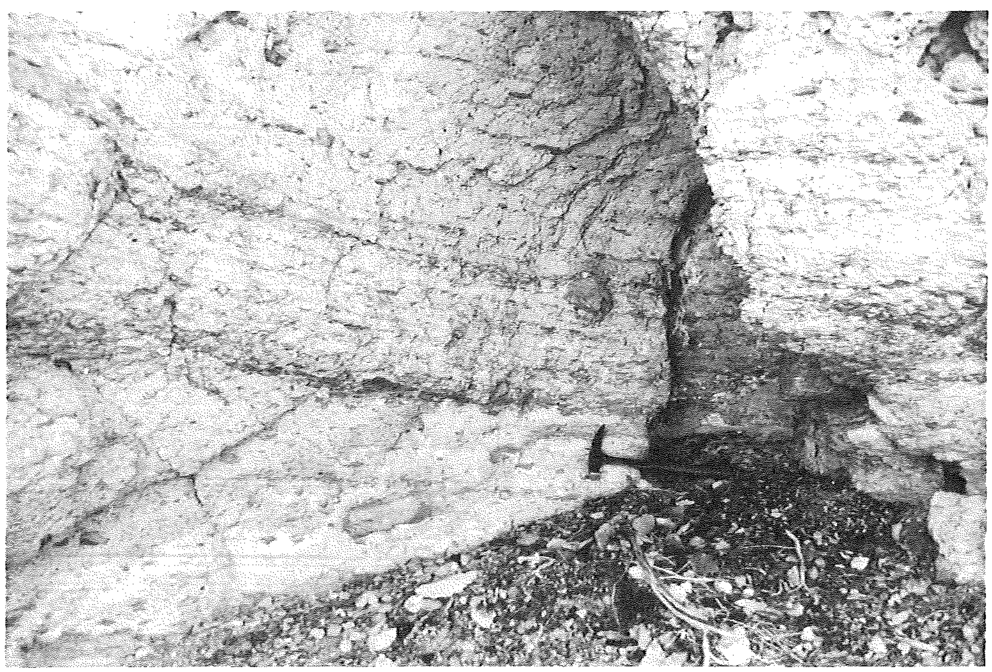


Figure 3. Part of a thick sequence of welded air-fall tuff of Trough Mountain, showing characteristic thin layering and lithic fragments. Relatively massive bed on which hammer rests is probably an interbedded ash-flow deposit. Location: about 3 km south of Trough Mountain, near "B" on Figure 1.

TABLE 1. CHEMICAL ANALYSES OF ROCKS FROM THE SOLDIER MEADOW AREA, NORTHWESTERN NEVADA

Sample no.	1	2	3	4	5	6	7
Field no.	M90-NG	M101B-NG	M62	M17-D-F	MO-1A-NG	MO-2-NG	M26
SiO_2	74.58	73.2	75.5	75.3	75.8	74.4	59.1
Al_2O_3	10.33*	10.3	10.9	10.5	11.4	11.2	15.7
Fe_2O_3	1.63		1.6	2.4			1.7
FeO	1.54	2.96†	1.1	0.44	1.82†	1.77†	5.1
MgO	0.05	0.05	0.08	0.08	0.12	0.12	2.4
CaO	0.13§	0.13	0.25	0.81	0.14	0.14	4.9
Na_2O	4.81	4.85#	4.3	4.1	4.6	4.3	4.1
K_2O	4.70	4.57#	4.5	4.5	4.7	4.8	3.0
H_2O+	0.80	..	0.40	0.57	..	..	1.4
H_2O-	0.01	..	0.10	0.63	..	..	0.19
TiO_2	0.17	..	0.23	0.18	..	..	1.6
P_2O_5	0.01	..	0.00	0.06	..	..	0.71
MnO	0.16	..	0.14	0.10	..	..	0.19
CO_2	..	..	<0.05	<0.05	..	..	<0.05
Cl	0.25	0.2	..	..	0.2	0.3	..
F	0.28	..	..	..	..	..	..
Subtotal	99.80**	96.26					
Less O	-0.18	-0.04					
Total	99.62	96.22	99.1	99.7	98.8	97.0	100.1
Ba (ppm)††	9	..	19	45	..	..	..
Sr (ppm)§§	≤2	≤2	4	12	∿2	≤2	438

.. = not determined.

* *Corrected for spectrographically determined Zr, Nb, and rare earth oxides.*

† *Total iron as FeO.*

§ *By x-ray fluorescence, atomic absorption, and electron microprobe methods (Noble and others, 1972).*

\# *By flame photometry, Lois Schlocker, analyst.*

** *Based on uncorrected Al_2O_3 value (10.68 wt percent).*

†† *By optical emission spectrography, J. C. Hamilton, analyst.*

§§ *By x-ray fluorescence methods, M. K. Korringa, analyst (Korringa, 1972).*

Description of analyzed samples

1. *Nonhydrated glass separate from a block of densely welded tuff from the ash-flow member of the Soldier Meadow Tuff, lat. 41°27'00" N., long. 119°09'15" W. Analyzed by the methods of Peck (1964), G. O. Riddle, analyst.*

2. *Nonhydrated glass separate from a large, dense collapsed pumice fragment in the air-fall member of the Soldier Meadow Tuff, lat. 41°26'55" N., long. 119°08'55" W. Analyzed by electron microprobe methods, M. K. Korringa, analyst (Korringa, 1972).*

3. *Densely welded, granophyrically crystallized tuff from the ash-flow member of the Soldier Meadow Tuff, at about lat. 41°20' N., long. 119°05' W. Analyzed by the method of Shapiro and Brannock (1962), supplemented by atomic absorption methods, P. Elmore, H. Smith, J. Kelsey, L. Artis, J. Glenn, and G. Chloe, analysts.*

4. *Dense, granophyrically crystallized lava from the lava member of the Soldier Meadow Tuff, lat. 41°27'20" N., long. 119°12'35" W. Analysts and methods of analysis same as for specimen 3.*

5. *Nonhydrated glass cores from cognate aphyric obsidian inclusion in the tuff of Trough Mountain, lat. 41°29'25" N., long. 119°07'20" W. Inclusion probably represents a blob of nonvesiculated magma (compare Gibson and Tazieff, 1967; Gibson, 1970). Analyst and method of analysis same as for specimen 2.*

6. *Nonhydrated glass from lithic fragment of aphyric obsidian contained in slightly welded tuff of Trough Mountain, lat. 41°26'40" N., long. 119°07'50" W. Analyst and method of analysis same as for specimen 2.*

7. *Phenocryst-poor, high-potash andesite intruding the Soldier Meadow Tuff, lat. 41°26'00" N., long. 119°10'00" W. Analysts and methods of analysis same as for specimen 3.*

elongate zone about 5 by 14 km in the central part of the known exposures of the unit and near the thickest sections. This zone is found along the western side of a north-south valley west of Trough Mountain and east of the Soldier Meadow lava. Partly welded air-fall tuff containing abundant lithic fragments as much as 60 cm in diameter is at least 20 m thick in two localities, 3 and 10 km south of Trough Mountain (Figs. 1, 3). Densely welded air-fall tuff also occurs locally in a small exposure about 35 m in diameter just south of the southern exposure of lithic-rich tuff (Fig. 1). The dense welding and the fact that the patch is not simply an erosional remnant but grades into nonwelded tuff at its margins both indicate that it was deposited near a vent.

North-trending dikes of the phenocryst-poor silicic lava were intruded south of Trough Mountain; they have locally contorted but generally steep north-trending flow foliation. North and northwest of Trough Mountain, similar intrusive rocks include breccia containing abundant fragments of tuff of Trough Mountain. Some of these lavas might fill tuff vents; vents may also be buried beneath the Soldier Meadow lava. Approximately north-trending Basin-Range faults may have controlled the trend of the vent system.

SOLDIER MEADOW TUFF

The Soldier Meadow Tuff was named by Noble and others (1970) for exposures surrounding Soldier Meadow, Nevada (Figs. 1, 2). They designated a type section at lat 41°22′30″ N., long 119°15′40″ W. The Soldier Meadow Tuff is here divided into three informal members. The stratigraphically lowest member is an ash-flow deposit with an original volume of about 50 cu km (void free). Near the center of its present exposures, about 6 km north of Soldier Meadow Ranch and within the immediate vicinity of the vents from which it was erupted, the ash-flow deposit is overlaid by as much as 60 m of nonwelded to densely welded air-fall tuff. This tuff, petrographically and chemically indistinguishable from the ash-flow tuff, probably comprises less than 1 cu km (void free). The upper member, not originally included in the Soldier Meadow Tuff by Noble and others (1970) but here assigned to the formation, consists of about 2 cu km (void free) of lava which intrudes and overlies the tuffs in the vent area. The lava is remarkably similar in chemistry, petrography, and physical appearance to the tuffs, differing from them mainly in its lack of eutaxitic structure and by the presence of well-developed flow structures. The lava and the underlying tuff form a single cooling unit almost everywhere.

Distribution

Although the air-fall tuff and lava members are present only in the vicinity of the vents, the ash-flow member of the Soldier Meadow Tuff is exposed over an area of about 1,500 sq km in the Calico Mountains and the western Black Rock Range (Fig. 2). Thickness variations in the unit exceed 100 m and reflect previously existing topography, caused at least in part by faulting. A clear example of this is found about 17 km south of Soldier Meadow. Here the unit covers a slightly older (post–Summit Lake Tuff) fault scarp; the top of the deposit is level, but its thickness increases from 10 m to more than 50 m within a lateral distance of about 50 m.

In exposures near its southern, eastern, and northeastern limits, the tuff is consistently less than about 30 m thick and is relatively porous. The most southwesterly outcrops, in the general vicinity of High Rock Lake (Fig. 2), show no such evidence of having been near the depositional edge of the unit. Furthermore, an air-fall tuff unit in High Rock Canyon at lat 41°20′30″ N., long 119°21′20″ W. contains abundant xenoliths of moderately to densely welded Soldier Meadow Tuff as much as 1 m in diameter. These large blocks probably did not travel far from their origin, and their presence indicates that the Soldier Meadow Tuff extends at least this far to the southwest, buried beneath younger rocks. There apparently was, however, an original embayment in the eastern limits of the formation, in part because the Soldier Meadow vents lie just west of a great thickness of tuff of Trough Mountain. Within the vent area, the ash-flow member of the Soldier Meadow Tuff thins eastward toward Trough Mountain, decreasing from over 50 m to 5 m or less, and apparently spread farther east only after flowing around this obstruction. Also, the lava member has a comparatively straight margin with very short and stubby flows on the east (Figs. 1, 4), suggesting that faulting along the western margin of Trough Mountain accentuated pre–Soldier Meadow topographic relief. Farther to the east and southeast, large rhyolite domes in the northern and central Black Rock Range almost completely blocked the spread of the tuff.

Description

Most of the Soldier Meadow Tuff is crystallized and is typically light blue, light gray, pinkish tan, or light green. Glassy pumice is pale tan, or yellow to green where altered, and vitrophyre is dark green or black. The unit weathers dark chocolate or reddish brown.

Pumice fragments comprise about 10 to 50 percent of the tuff. Small xenoliths, many less than 3 cm in diameter, make up 1 percent or less of the tuff. However, within 8 km of the vents, they may be as much as 10 cm in diameter and comprise as much as 10 percent of the rock (Korringa, 1972, Table 2). Cognate lithic fragments of Soldier Meadow lithology are widespread and compose more than 50 percent of certain ash flows. Within the air-fall

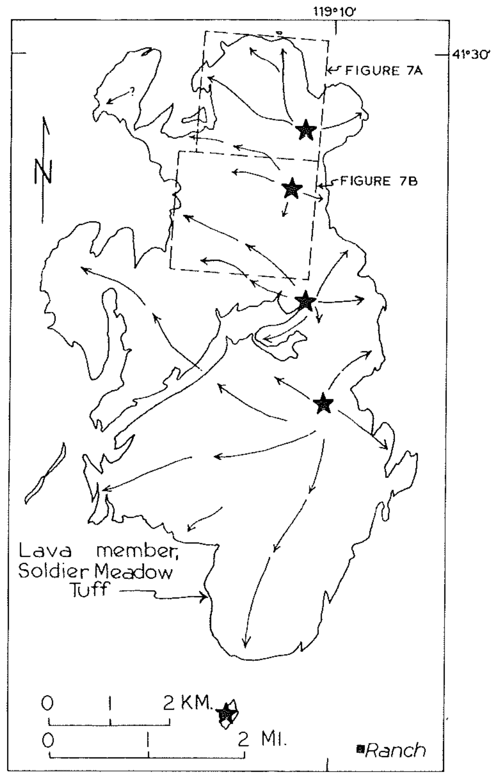


Figure 4. Generalized map, showing direction of movement of flow lobes of the lava member of the Soldier Meadow Tuff. Stars show location of vents. See Figure 1 for detailed geology. Dashed lines indicate areas covered by Figure 7A and 7B.

deposits, cognate lithic fragments are particularly abundant (Fig. 5), and some are as much as 60 cm in diameter. One block, which was partly protected by the surrounding crystallized tuff from ground-water alteration, yielded numerous small (<3 mm diam) cores of nonhydrated glass, an analysis of which is given in Table 1 (analysis 1). Another analysis (sample 2) is of nonhydrated glass cores from dense, glassy pumice fragments in the air-fall member.

The ash-flow sheet is composed of many individual flows. Some ash flows or groups of flows are distinguished from adjacent layers by different proportions or average sizes of pumice fragments. Zones containing very abundant cognate lithic fragments may represent concentrations of heavier materials at the bases of individual ash flows. In places, there are partial cooling breaks where an ash flow or part of a flow is noticeably more porous than others. Between many ash flows, there are laterally persistent partings associated with a nonresistant zone of rock about 3 to 25 cm thick. Some partings occur along layers that are exceptionally crystal rich, containing more than 40 percent phenocrysts. Other horizontal joints of uncertain origin are not laterally continuous. The 125-m type section was measured by hand leveling, and a count of only those horizontal joints which are continuous and occur between layers of differing lithologic character indicates that this section probably includes at least 60 ash flows.

Most of the Soldier Meadow Tuff is partially welded, and parts of sections more than 50 m thick are densely welded. Related nonwelded pumice and ash at the base are absent or very thin. As much as 10 m of poorly welded tuff was found preserved at the top of the ash-flow sheet in a few localities, and presumably originally covered the entire ash-flow member. Both the ash-flow and lava members locally have well-developed columnar joints (Fig. 6).

The lava member has an average thickness of about 35 m and covers an area of about 40 sq km centered several kilometers N. 10° W. of Soldier Meadow Ranch. The contact is sharp and, in most cases, can be located within a few centimeters to a meter. As mentioned above, the tuff and lava form a single cooling unit; in most places, rocks on both sides of the contact are granophyrically crystallized. Locally there is a zone of preferential weathering 25 to 75 cm thick directly above the contact; in some places, there is a basal flow breccia in the lava as much as 5 m in thickness. Where the outer edge of the lava is glassy, it may overlie either glassy or crystallized tuff.

The lava possesses well-developed large- and small-scale flow foliation. The flow planes parallel the lower surface of the lobes, steepen progressively to become perpendicular to the outer surfaces, and in the center of a lobe are commonly vertical and parallel to the long axis of the lobe. The general configuration of flow planes in a lobe is spoon shaped, with most dips toward the center of the flow and (or) back toward its source (Figs. 1, 6). This is in agreement with flow-foliation patterns determined in a number of other lavas (for example, Christiansen and Lipman, 1966; Benson and Kittleman, 1968). Zones of highly contorted

Figure 5. Thin layering in poorly welded, glassy air-fall member of the Soldier Meadow Tuff, clearly visible in center of photograph. Some lithic fragments in a very lithic-rich bed are indicated by arrows. About 6.5 km north of Soldier Meadow, near "B" and to the left of "A" on Figure 1. This locality is the white patch in the foreground of Figure 8.

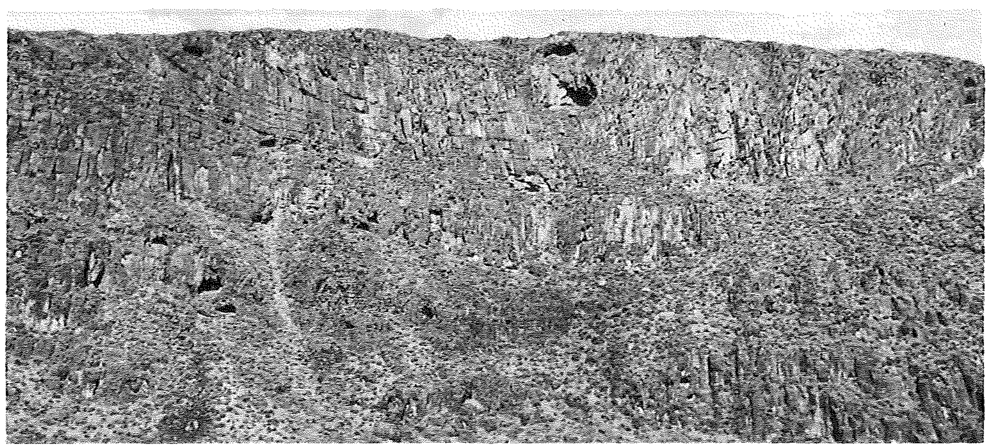


Figure 6. Flow foliation in lava member of the Soldier Meadow Tuff. The cliff (visible portion is about 60 m high), which provides a cross section of the center of the southwesternmost flow lobe, is largely the result of movement on a normal fault. Foliation is broadly U shaped; note inward dips and upward steepening of foliation. Columnar jointing is visible throughout the exposure. View is northeast, about 400 m east-northeast of letter "A" of the cross-section line on Figure 1.

lava also occur locally. The outermost parts of the flows are generally not preserved, although glassy zones at the top and edge of the lava flows in some localities indicate that only a small thickness has been eroded from the original surface. Where erosion has been minor, large-scale patterns in the lava flows (Fig. 7) may include pressure ridges.

Vent Region

By use of large-scale flow banding, visible on and easily measured from aerial photographs, combined with field measurements, the flow pattern and points of origin of the lava flows can be determined accurately. The lobes originate from four zones characterized by concentric, circular to oval, near-vertical flow foliation (Figs. 1, 7). These zones mark the locations of the vents. A much smaller, plug-like fifth vent is located southwest of the main four (Fig. 1; about 2 km west of Soldier Meadow Ranch). Near-vent lava is typically very vesicular and contains breccia; it has horizontal, vertical, or highly contorted foliation.

The southernmost of the four major vents is the source of six lava lobes (Fig. 4). The eastern side of this vent is faulted and eroded, exposing part of its internal structure (Fig. 8). At its northeastern edge, in the most deeply eroded levels beneath the lava, the ash-flow member is exposed, dipping gently away from the lava vent and resting on nonwelded tuff of Trough Mountain. Here the ash-flow member is primarily crystallized, although it is only 5 m thick. Exposed above the ash-flow member, there is approximately 50 m of poorly welded, thin-bedded, air-fall tuff (Fig. 5). Some of the more massive beds may be interbedded ash-flow deposits. Some of this tuff is glassy, although many parts have undergone both vapor-phase crystallization of the pumice and later, postcooling, ground-water alteration. This lower part of the air-fall tuff member contains abundant lithic fragments, many as large as 25 cm in diameter; it thins abruptly eastward, dipping about 20°, generally away from the inferred center of eruption. Above this poorly welded air-fall tuff deposit, in exposures nearer the center of the lava vent, there is a 5-m zone of nonwelded, glassy pumice and ash. This is covered by 3 m of moderately to densely welded, crystallized, thin-bedded air-fall tuff with dips of 20° to 30°. Individual beds in these rocks average 8 cm or less in thickness, and some consist almost entirely of pumice. East of the next lava vent to the north, similar densely welded air-fall tuff dips 40° toward that vent (Fig. 1). The attitudes of the overlying lava flows indicate that these dips are mostly original. Therefore, these sequences probably represent tuff "cones" with outward-dipping tuff on the flanks, mantled with more densely welded air-fall layers, at least in part within the craters themselves. The lava probably filled the craters and then overflowed to form the elongate lobes.

The generally greater size and concentration of lithic fragments within the vent area has been noted above. There is also a decrease in the proportion of groundmass to phenocrysts with increased distance from the vent area (Korringa, 1972, Table 2 and Fig. 23), probably caused by loss of ash during eruption and transport (compare Walker, 1972). This variation is the opposite of that found in certain other units (Fisher, 1966; Lipman, 1967), in which the pattern is interpreted to be the result of density sorting and preferential deposition of crystals during early stages of transport.

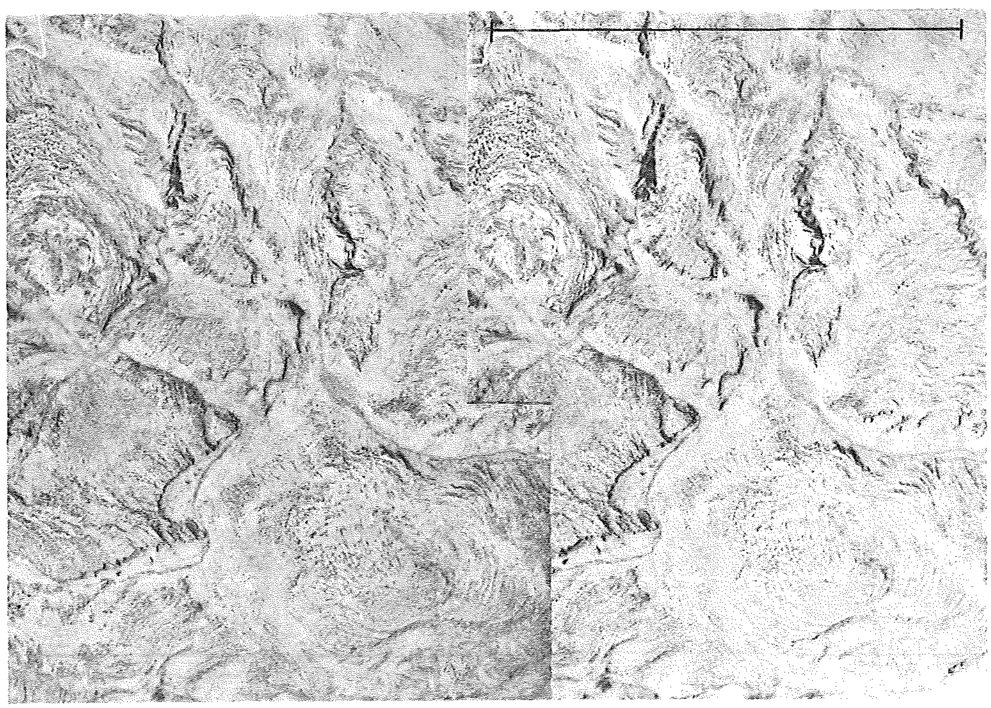
There is no evidence that this vent area is part of a caldera, resurgent caldera, or other type of volcano-tectonic depression. The faults of the area and the alignment of the vents follow regional trends, and no concentric or radial fractures could be found to correlate with either doming or collapse. If readjustment at some depth occurred after eruption of the Soldier Meadow Tuff, it was probably taken up at the surface by slight foundering on a regional scale in a manner indistinguishable from other Basin-Range block faulting.

Petrography

Except where noted, the following comments apply to both the lava and the tuff. Microprobe procedures and analyses referred to are given in Korringa (1972).

The Soldier Meadow Tuff contains an average of 13 percent sanidine and 9 percent quartz phenocrysts; less than one percent each of ferrorichterite, sodic ferroaugite, magnetite, and ilmenite; rare composite grains composed of granophyrically intergrown quartz and sanidine; and rare aenigmatite, zircon, and biotite crystals. Many of the phenocrysts in the tuff are broken, and small slivers and chips are common, as well as larger fragments; most

A



B

Figure 7. Stereographic pairs of aerial photographs showing flow patterns in the lava member of the Soldier Meadow Tuff. Vents are located in the lower left corner of A and lower right of B. North is to the right. See Figure 4 for locations. Bars are approximately 1 km long.

phenocrysts in pumice fragments and the lava member are unbroken.

Unzoned sanidine occurs as euhedral to partially resorbed tabular or blocky crystals as much as 3 mm long. Very fine grid twinning and simple twins are abundant. Although the crystals are optically homogeneous, fine-scale exsolution has probably taken place, as the phenocrysts typically display brilliant blue chatoyancy. Microprobe analysis corroborates lack of zoning and, along with x-ray fluorescence data (Korringa, 1972), indicates a composition of about $Ab_{54}Or_{46}An_{0.1}$ (weight percent). Optic axial angle is -32.6 ± 1.6 degrees. In the crystallized rocks, some sanidines have irregular, optically continuous overgrowths less than 0.1 mm wide, composed of slightly more sodic (Ab_{58}) alkali feldspar.

The quartz is commonly smoky and occurs as euhedral hexagonal bipyramids 1 to 2.5 mm in diameter or as crystal fragments. It is more commonly resorbed than sanidine and also has a greater proportion of optically continuous overgrowths of groundmass quartz.

Amphibole phenocrysts compose less than 1 percent of the rock. They are euhedral to subhedral six-sided prisms as much as 1 mm in length. Microprobe analysis shows that there are actually two similar ferrorichterites of approximate molecular formulas $Na_{1.26}K_{0.11}Ca_{0.93}(Mg_{2.39}Fe_{2.47}Ti_{0.13}Mn_{0.26})[Si_{7.52}Al_{0.30}O_{22}]F_{0.83}Cl_{0.01}OH_{0.99}$ and $Na_{1.16}K_{0.14}Ca_{0.94}(Mg_{1.47}Fe_{3.49}Ti_{0.16}Mn_{0.23})[Si_{7.29}Al_{0.36}O_{22}]F_{0.79}Cl_{0.02}OH_{1.01}$. There is slight zoning toward more sodic and iron-rich compositions near some grain margins. Both amphiboles have pleochroic schemes of α = green, dark brown, very dark brown; β = red brown, gray; γ = pale yellow brown; and have anomalous extinction.

Anhedral to subhedral clinopyroxene, 0.5 mm in average length, is less abundant than the amphiboles. Microprobe analysis shows the pyroxene to be a sodic ferroaugite with an average molecular formula of $(Ca_{0.65}Na_{0.13}Fe_{0.86}Mg_{0.28}Mn_{0.09}Ti_{0.01})[Si_{1.99}Al_{0.01}O_6]$. It has strong deep-green to pale-green or yellow pleochroism. Both amphibole and pyroxene may be partly altered to iron oxide or yellow fibrous phyllosilicate.

Two iron-titanium oxides are present. Magnetite ($Mt_{55}Usp_{45}$), abundant as phenocrysts and as an alteration, contains exsolution branches of ilmenite in a few percent of the

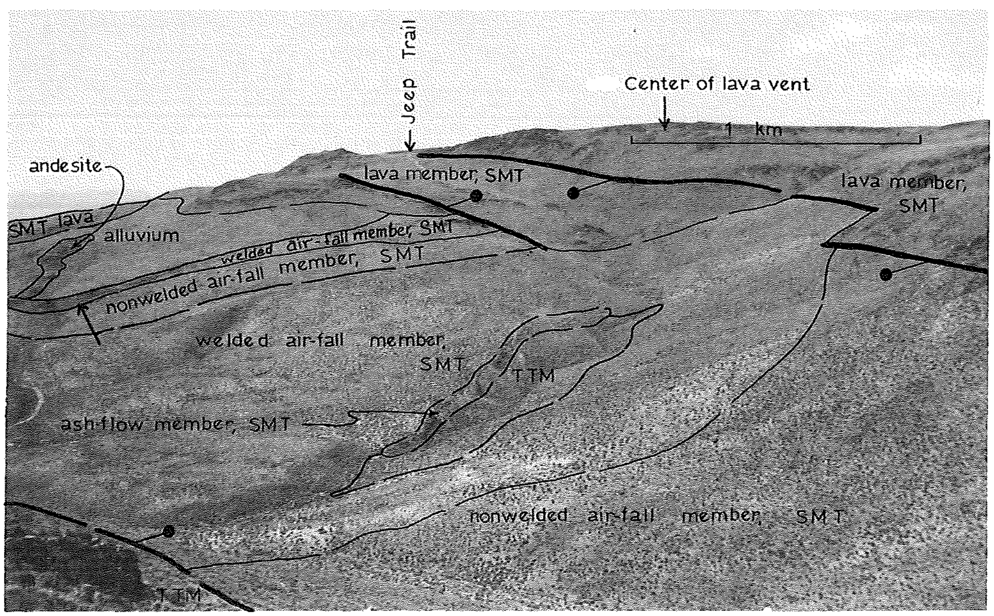


Figure 8. View south-southeast at southernmost of four major lava vents of Soldier Meadow Tuff, about 6 km north of Soldier Meadow Ranch. Faults shown by heavy lines, contacts by light lines. Large arrow on left side of photograph indicates location of block containing nonhydrated glass (Table 1, analysis 1). SMT = Soldier Meadow Tuff. TTM = tuff of Trough Mountain.

grains observed. The phenocrystic ilmenite ($Ilm_{93}Hem_7$) is much less abundant.

Planar orientation of deformed pumice fragments, shards, and of elongate phenocrysts is generally apparent in thin sections even in crystallized specimens of the tuff. Most of the groundmass of both tuff and lava is granophyrically crystallized in the sense that it is composed of intimate intergrowths of alkali feldspar and apparently primary quartz (Smith, 1960b, p. 152). Complete gradations occur between granophyric intergrowths, spherulitic structures, and anhedral mosaics with curved or interdigitating grain boundaries (compare Barker, 1970; Lofgren, 1971). Tablets or needles of sodic amphibole with blue to purple to straw, or green to brown, pleochroism are present in the groundmass of 33 out of 36 thin sections of crystallized specimens. Smaller crystals of euhedral, pleochroic (blue-green to yellow-green), highly birefringent clinopyroxene occur in the groundmass of more than one-third of the crystallized specimens. These same minerals are also found, along with rare tridymite, as vapor-phase growths.

Welding and granophyric crystallization are characteristic of the ash-flow member even where it is only 5 m thick. Noble (1970a) has noted that granophyric crystallization in relatively thin ash-flow sheets is characteristic of peralkaline tuffs, and Lofgren (1971) has shown experimentally that excess alkalies accelerate the devitrification process.

Chemistry

The Soldier Meadow Tuff is a comendite whose low MgO, CaO, Sr, and Ba contents (Table 1), for example, compared to "average granites" (Taylor, 1964), indicate a very large amount of fractional crystallization prior to eruption (Noble and others, 1969; Korringa and Noble, 1971). Plots of Rb versus Zr, and Rb versus Fe (Fig. 9) show coherent trends within the unit. These can be explained by several factors: (1) dilution of Rb, Zr, and Fe by increased percentages of phenocrysts, due to glass-crystal sorting during eruption and deposition, (2) in some cases, dilution by silica added by ground water, and (3) crystal fractionation, which increased the Rb, Zr, and Fe in the melt by removal of mainly alkali feldspar and quartz. Some of the spread in the Rb/Fe plot is probably the result of analytical difficulties in the determination of iron (Leake and others, 1969).

The tuff and lava members have limited overlapping compositional ranges, which would be smaller if corrected for varying proportions of crystals. Specimens plotted in Figure 9 represent a wide geographic coverage as well as various stratigraphic positions. The lava plots at the "more differentiated" end of the trend; this is the only consistent vertical compositional trend (Korringa, 1972). It is probable that if there were any systematic vertical compositional zoning, it has been blurred by the large variations due to crystal sorting.

The peralkaline composition of the Soldier Meadow Tuff probably contributed to the relatively fluid behavior of the lava, which

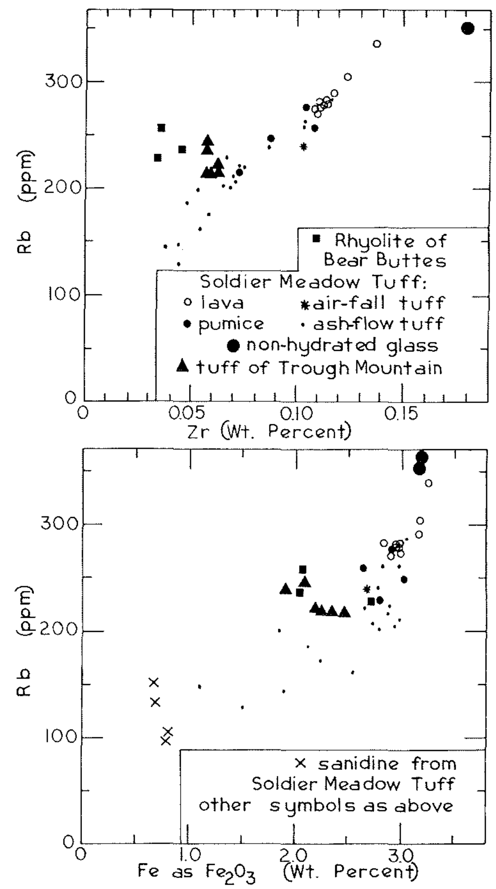


Figure 9. Plots of Rb versus Zr, and Rb versus total Fe as Fe_2O_3 for 42 whole-rock analyses, and for sanidine and nonhydrated glass from the Soldier Meadow Tuff. A few points have been shifted slightly for clarity in plotting. X-ray fluorescence data, M. K. Korringa, analyst (Korringa, 1972).

formed quite thin, elongate lobes for such a silicic magma (Shaw, 1965).

Analyses of the rhyolite of Bear Buttes and the tuff of Trough Mountain plot somewhat off the Soldier Meadow trends, particularly in the Rb/Zr graph. The consistently higher Rb/Zr ratio shown by these two units probably reflects earlier and more prolonged precipitation and removal of zircon than in the Soldier Meadow Tuff. Since formation of zircon is apparently inhibited by peralkaline conditions (Dietrich, 1967), the rhyolite of Bear Buttes and the tuff of Trough Mountain probably became peralkaline at a later stage in their histories than did the Soldier Meadow Tuff.

Chemical similarity between the tuff and lava of the Soldier Meadow Tuff is further shown by the analyses (Table 1, analyses 2 and 3) of two widely separated, dense, granophyrically crystallized specimens: one from the ash-flow member and one from the lava member. Minerals also show remarkable similarity between the two types of rock in the unit. Microprobe analyses (Korringa, 1972) of amphibole, pyroxene, and both iron oxides from a lava and a tuff specimen are identical within the precision of the analyses. Sanidine from the tuff and lava members have statistically identical optic axial angles of approximately −33 degrees (Korringa, 1972, Table 12).

The compositions of the iron-titanium oxide pair in the Soldier Meadow Tuff represent an equilibrium temperature of approximately 825°C and $\log_{10}$ of oxygen fugacity of −14, according to the experimental data of Buddington and Lindsley (1964).

RHYOLITE OF BEAR BUTTES

Peralkaline rhyolite intrudes and overlies the Soldier Meadow Tuff at Bear Buttes (Fig. 1), and similar lava flows are abundant farther north and northwest. The rhyolite is generally crystallized and pale gray, blue-gray, or tan in color and weathers medium to dark brown. It contains about 9 percent subhedral sanidine phenocrysts as much as 3 mm long, and 7 percent euhedral to partially resorbed quartz as much as 2.5 mm in diameter. These rocks differ in several respects from the lava member of the Soldier Meadow Tuff. The sanidine has a consistently lower optic axial angle (−27.7 ± 1.4 degrees; Korringa, 1972) and is slightly less abundant with respect to quartz than in the Soldier Meadow Tuff. X-ray fluorescence analyses (Fig. 9) show that these rocks also have generally lower Fe and Zr contents and Rb/Zr and Rb/Fe ratios than the lava member of the Soldier Meadow Tuff. Finally, flow foliation is much better developed in the lava member of the Soldier Meadow Tuff than at Bear Buttes.

DISCUSSION

Summary of Evidence for a Linear Vent

A number of lines of evidence indicate that the tuff and lava members of the Soldier Meadow Tuff were derived from the same magma and that both were erupted from the same linear-vent region.

The lava vents are located near the center of the ash-flow sheet and west of the obvious obstructions to its easterly spread. Other evidence for eruption of the ash flows from this area includes the decrease in the proportion of groundmass away from this area (probably indicating more prolonged transport of the ash flows outside of the vent area) and the fact that although lithic fragments in the tuff are widely distributed, xenoliths are consistently larger and more abundant within 8 km of the vents.

Appreciable thicknesses of air-fall tuff are apparently restricted to the vent area. The presence of welded air-fall tuff is of particular importance, since air-borne pyroclastic materials would presumably cool rapidly enough to prevent welding more than about 1 km from their source. The dips of welded air-fall tuff beds are consistent with the formation of rings of tuff around the vents.

The virtually identical phenocrysts, groundmass and vapor-phase minerals, and the continuity of chemical composition in all lithologic types in the Soldier Meadow Tuff are strong evidence that they represent the same magma. The fact that they form a single cooling unit shows that they were produced during essentially continuous eruption. The distribution and flow foliation patterns in the lava clearly indicate that it was extruded from five aligned vents (Figs. 1, 4, 7), and it is concluded that these vents were connected to a common magma reservoir from which the entire Soldier Meadow Tuff was erupted.

Although it is not possible to completely rule out contributions to the ash-flow sheet by other, undiscovered, vents, detailed study of numerous tuff outcrops revealed no evidence of another eruptive center.

The stratigraphic sequence described above for near-vent deposits is interpreted as representing decreasing intensity of eruption. After the numerous ash flows were forcibly expelled, the much more local air-fall tuff apparently accumulated as small cones. The densely welded air-fall tuff near the top of the tuff sequences was either considerably hotter or less exposed to air cooling than the earlier air-fall tuff. The rate of vesiculation or amount of volatiles decreased until only a vesicular lava was extruded.

It originally was suspected, because of the lack of a cooling break between the tuff and lava, that rocks of the lava member might be welded tuff which underwent laminar flowage in the final stages of deposition (compare Hoover, 1964; Sargent and others, 1966; Walker and Swanson, 1968). Workers should be alert to avoid such misinterpretation in more poorly preserved units.

Tectonic Setting

Ash-flow tuff is common in regions undergoing horizontal extension such as active rift zones and the Basin and Range province during the late Cenozoic (for example, Christiansen and Blank, 1969; King, 1970; Smith and Bailey, 1968). Some ash-flow eruptions have occurred concurrently with high-angle faulting: for example, certain of the Pliocene tuff sheets in Harney County, Oregon, were deposited penecontemporaneously with faulting and basin collapse (Walker, 1969, p. C9). Regions of extensional faulting do contain equant calderas. Some occur in relatively unfractured blocks; others, such as the Timber Mountain caldera in southern Nevada, are superimposed on the regional fault pattern (Christiansen and others, 1965). These collapse structures probably reflect rapid eruption from relatively shallow magma chambers. The extension and accompanying faulting may facilitate the rise of magma in some situations. In other situations, the faults may provide an escape route to the surface for magma from great depth—and a shallow chamber may never form. Thus the alignment of the Soldier Meadow Tuff vents appears to be a result, but not a necessary consequence, of the extensional faulting.

There are no concentric fractures due to doming or collapse related to the Soldier Meadow Tuff, nor is there any evidence of caldera or major graben collapse including, or adjacent to, the vent region, even though the lack of a cooling break between the tuff and lava members indicates relatively rapid and continuous eruption. The lack of collapse features can be interpreted in various ways. Eruption may have been from a chamber so broad with respect to height that the effects of any doming and subsequent deflation were regional and thus indistinguishable from the block faulting. In a narrow, dike-like chamber, the effect of extrusion might have been taken up by dominantly horizontal slumping. Surface readjustments after venting of a very deep magma chamber might also have been spread over a large region. The large amount of resorption of the quartz and sanidine phenocrysts in the Soldier Meadow Tuff may be an indication of eruption of a water-undersaturated magma from a relatively deep chamber (Noble, 1970b). Finally, regardless of depth or geometry of the chamber, and despite rapid drainage by eruption of tuff and lava, continuing high magma pressure could have greatly reduced the likelihood of any collapse.

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